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Effects of grasp compatibility on long-term memory for objects☆

Ivonne Canits*, Diane Pecher, René Zeelenberg

Erasmus University Rotterdam, The Netherlands

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ABSTRACT

Previous studies have shown action potentiation during conceptual processing of manipulable objects. In four experiments, we investigated whether these motor actions also play a role in long-term memory. Participants categorized objects that afforded either a power grasp or a precision grasp as natural or artifact by grasping cylinders with either a power grasp or a precision grasp. In all experiments, responses were faster when the affordance of the object was compatible with the type of grasp response. However, subsequent free recall and recognition memory tasks revealed no better memory for object pictures and object names for which the grasp affordance was compatible with the grasp response. The present results therefore do not support the hypothesis that motor actions play a role in long-term memory.

Grounded cognition theories suggest that cognitive processes such as memory and language share processing mechanisms with perception and action (Barsalou, 2008). On this account, conceptual knowledge is not purely represented in abstract symbols but instead is the reactivation of perceptual and motor experiences related to the concept; memory for a concept consists of information from different modalities that is distributed across sensory-motor systems (Barsalou, 1999). In some versions of this account, the main function of concepts is to support our interactions with the environment (Glenberg, 1997; Glenberg, Witt, & Metcalfe, 2013). Thus, motor information should be particularly important for object concepts. When perceiving objects, we purportedly do not just passively perceive them as such but we perceive their manipulable properties (Gibson, 1979). According to Glenberg, these perceived properties are combined with memories of prior actions in order to support actions.

Thus, according to the grounded view, motor actions have a central role in object knowledge. Studies using neuroimaging methods have indeed shown activation of motor or premotor cortical areas when participants process objects (Buccino, Sato, Cattaneo, Rodà, & Riggio, 2009; Chao & Martin, 2000; Creem-Regehr & Lee, 2005; Martin & Chao, 2001; Martin, Wiggs, Ungerleider, & Haxby, 1996). Moreover, results from many studies have indicated that representing objects potentiates actions that are compatible with those objects (Bub & Masson, 2010a; Bub, Masson, & Cree, 2008; Ellis & Tucker, 2000; Masson, Bub, & Breuer, 2011; Tipper, Paul, & Hayes, 2006; Tucker & Ellis, 1998; but see Masson, 2015; Proctor & Miles, 2014). Tucker and Ellis (2004; see also Girardi, Lindemann, & Bekkering, 2010) found compatibility effects when participants categorized objects on photographs as either natural or artifact by using either a power grasp or a precision grasp. Participants responded faster when the response grasp was compatible with the size of the object (and thus the type of grasp that the object afforded, for example a precision grasp for a *needle*). Several findings support the idea that grasp actions are activated as part of the concept. Compatibility effects are found even when the stimuli are words referring to manipulable objects (Bub et al., 2008; Bub & Masson, 2010b; Glover, Rosenbaum, Graham, & Dixon, 2004; Masson, Bub, & Lavelle, 2013; Masson, Bub, & Warren, 2008; Rueschemeyer, van Rooij, Lindemann, Willems, & Bekkering, 2010; Tucker & Ellis, 2004) or when action is not physically possible because the object is outside reaching distance (Tucker & Ellis, 2001; but see Costantini, Ambrosini, Tieri, Sinigaglia, & Committeri, 2010; Ferri, Riggio, Gallese, & Costantini, 2011). Bub et al. (2008) showed that grasp compatibility effects are not due to visual similarity between the grasping device and the visual object stimulus, because the compatibility effect was absent when participants had to merely touch the device rather than grasp it. Furthermore, the grasp compatibility effect is found even though size is task-irrelevant (Bub et al., 2008; Tucker & Ellis, 2004). This has been taken to suggest that the grasping action is part of the knowledge that is activated for a concept. Grasp compatibility effects suggest that actions are activated automatically, that is, actions are activated even if the task does not require it, although some studies have shown that activation of actions can be modulated by context (Borghi, Flumini, Natraj, & Wheaton, 2012; Borghi & Riggio, 2015; Jax & Buxbaum, 2010; Kalenine, Shapiro, Flumini, Borghi, & Buxbaum, 2014; Taylor & Zwaan, 2010; Yoon, Humphreys, & Riddoch, 2010). Further support comes from studies that show negative effects of motor-interference on

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* Corresponding author at: Psychology Department, Erasmus University Rotterdam, Postbus 1738, 3000 DR Rotterdam, The Netherlands.
E-mail addresses: canits@ese.eur.nl (I. Canits), pecher@essb.eur.nl (D. Pecher), zeelenberg@essb.eur.nl (R. Zeelenberg).

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processing of concepts (Witt, Kemmerer, Linkenauger, & Culham, 2010; Yee, Chrysikou, Hoffman, & Thompson-Schill, 2013; but see Matheson, White, & McMullen, 2014), and a TMS study by Buccino et al. (2005; but see Pelgrims, Olivier, & Andres, 2011) showing differential modulation of the hand and foot muscle activity when participants read sentences describing actions with hand and foot related objects. These findings suggest that retrieval of knowledge and performing actions share processing mechanisms.

Given that grasping actions appear to constitute a significant part of conceptual memory, the question arises what their role is for other types of memory. In general, conceptual memory and episodic memory are strongly intertwined and may even be indistinguishable (Anderson & Ross, 1980; Dosher, 1984; Glenberg, 1997; Hintzman, 1986; McKoon, Ratcliff, & Dell, 1986). If potential actions are automatically activated when people identify objects, grasping actions could be encoded in memory traces and support short-term and long-term memory. Research on the role of actions in short-term memory for objects has shown mixed results. Support for a role of motor actions was provided by Apel, Cangelosi, Ellis, Goslin, and Fischer (2012) who required participants to keep instructions in working memory about how to move cups across a displayed grid. The handles of those cups could be at either the left side or the right side of the cup. Participants' memory span was worse when the objects' handles were spatially incompatible with the hand used in the instruction actions. Downing-Doucet and Guerard (2014) showed an effect of motor similarity on immediate order memory for pictures of objects. Participants studied lists of pictures of objects that were associated with several types of grasps (i.e., a leaf associated with a precision grip). A short video of a hand performing a grasping movement, either similar or dissimilar to how the object can be grasped, was shown prior to the presentation of each object. Afterwards, participants were immediately presented with the same objects and then had to indicate the order of object presentation. Participants had worse immediate order memory for pictures of objects that shared the same grasping action compared to objects that required different grasps. This interference effect suggests that participants use motor information elicited by the objects to retain the items in memory. In a second experiment, the effect of grasp similarity disappeared when the participants performed a concurrent motor task, suggesting that the effect of grasping similarity was due to involvement of the motor system (see also Guérard & Lagacé, 2014; Lagacé & Guérard, 2015, for similar results). It should be noted, however, that Downing-Doucet and Guérard did focus attention on the object's grasp and the grasp similarity between items by presenting the short videos of a hand making a compatible grasping movement before each object picture. Therefore, these results do not address the question of whether motor actions were spontaneously activated and encoded in memory. Moreover, several studies from our lab (Pecher, 2013; Pecher et al., 2013) obtained evidence that does not support the idea that memory for objects relies on the motor system. In these studies motor-interference tasks did not interfere more with memory for manipulable than nonmanipulable objects. For example, participants were shown several objects and had to keep these in short-term memory. Some objects had hand actions associated to them, for example *hammer* or *scissors*, whereas other objects did not, for example *traffic sign* or *chimney*. If motor actions are automatically recruited for concepts, a concurrent hand movement task should have interfered with activation of motor actions and thus resulted in worse performance for objects that have actions associated to them than for objects that do not have actions associated to them. That we did not find such interaction suggests that the motor system does not contribute to object memory. We also found that there was no memory benefit of performing a compatible grasping action during study compared to an incompatible grasping task (Quak, Pecher, & Zeelenberg, 2014). Thus, some studies showed a role of motor actions for object memory, but others did not.

This mixed state of affairs might be due to the use of short-term memory tasks. In general, research on working memory shows that interference tasks only decrease memory performance if the stimulus and the interfering task share a format (Baddeley, 2003). For example, spatial interference tasks interfere with memory for spatial information but not with memory for (non-spatial) visual information. Moreover, short-term memory might rely mostly on maintenance of the surface properties (orthography, phonology or perceptual characteristics) of the stimulus rather than their meaning (Baddeley, 1966). In a short-term memory task for visually presented objects, motor actions are not task-relevant and the shape and color of the object might just be sufficient to memorize the objects.

In long-term memory, however, conceptual properties of stimuli should be more important. First, as discussed earlier in this paper, perception of manipulable objects seems to activate grasping actions. If these actions are activated automatically, it would be reasonable to assume that they become part of the memory for that object. According to some grounded cognition theories (e.g., Barsalou, 2008; Glenberg, 1997; Glenberg et al., 2013), action information should become part of the object memory, as the action information will serve future interaction with that object. Second, there is an indication for a role of the motor system when participants learn about object functions. For example, Paulus, Lindemann, and Bekkering (2009) showed that participants were slower to retrieve knowledge of the function of recently learned objects when they had performed an interfering hand motor task during learning, compared to a foot motor task or attentional task. Because the functional object knowledge was novel, this finding indicates that the motor system also supports learning when the knowledge is not based on previous motor experiences.

The study by Paulus et al. (2009) thus indicates that the motor system might support memory for object related actions. Very little evidence is available for the role of the motor system in long-term memory for objects. Only two studies that we are aware of have investigated the influence of motor actions on long-term memory for familiar manipulable objects (Guérard, Guerrette, & Rowe, 2015; Van Dam, Rueschemeyer, Bekkering, & Lindemann, 2013). Van Dam et al. found that participants had better recognition memory for studied words denoting objects when the motor task performed during the retention phase (i.e., after initial encoding of all to-be-remembered stimuli) was compatible with the object's affordance (e.g., twisting for *screwdriver*) than when it was incompatible (e.g., pressing for *screwdriver*). Guérard et al., on the other hand, did not obtain evidence that motor actions play a role in long-term memory. They presented pairs of object pictures in action congruent or incongruent positions (e.g., a wine bottle above or below a wine glass). They assumed that seeing the objects in action congruent positions would activate motor actions more strongly than seeing the objects in incongruent positions, and that a concurrent motor-interference task would therefore have a more detrimental effect on memory for congruent than incongruent pairs. Although they did find the predicted interaction in a short-term memory task, no such effect was obtained in a long-term memory task. Given the large number of studies that have investigated the role of the motor system for conceptual memory it is remarkable that there are so few studies that have investigated its role for long-term memory. In addition, the conflicting results both in short-term and long-term memory studies raise the question how important the motor system is for memory. The current study thus aimed to test whether activated motor actions support long-term memory of objects.

We adopted the stimulus-response grasp compatibility paradigm (Tucker & Ellis, 2004) and extended it to include a free recall memory test. During study, participants categorized photographs of objects that afforded different grasps as natural or artifact, just as was done by Tucker and Ellis (2004). As response devices we used a thick graspable cylinder and a thin graspable cylinder in order to manipulate the compatibility between the object's grasp (power or precision) and the type of grasp response (power or precision). One potentially important difference between Van Dam et al. (2013) and Guérard et al. (2015) was that in Van Dam et al.'s study, participants performed actual actions whereas Guerard et al. only showed photographs that may or may not have activated actions. Therefore, we used this response device so that participants were preforming actions without necessarily being aware that action compatibility was part of the design. We had two aims with this study task. First, it allowed us to verify that visual objects potentiate compatible grasp responses, as Tucker and Ellis (2004) showed, even when action is task-irrelevant. Second, it also served as a manipulation of action compatibility, similar to Van Dam et al. (2013; for a manipulation of action compatibility in a short-term memory task see Lagacé & Guérard, 2015; Quak et al., 2014) who manipulated action compatibility after initial encoding. If presentation of visual objects in a conceptual task automatically activates potential motor actions we expect to replicate Tucker and Ellis' finding that response times are faster when the object grasp and the response grasp are compatible than when they are incompatible. In order to test the hypothesis that the motor system supports long-term memory, we then presented participants with an unexpected free recall test. The memory test was unexpected to prevent any intentional memorization strategies based on the grasping response. We expected that incompatible grasps would interfere with activation of motor actions and that such interference would result in a less complete memory trace for those objects. We therefore expected better memory for stimuli in the compatible condition than for stimuli in the incompatible condition.

1. Experiment 1

1.1. Method

1.1.1. Participants

Forty psychology students of the Erasmus University Rotterdam participated in the experiment for course credits. Four participants were left-handed. Participant recruitment and testing followed the university ethical guidelines.

1.1.2. Materials

A set of 80 pictures was created. Forty were pictures of natural objects (e.g., *apple*, *cherry*). The other 40 were pictures of artificial objects (e.g., *plunger*, *pencil*). Within each category (natural or artificial), half of the objects afforded a power grasp (picked up with a whole hand) and the other half afforded a precision grasp (picked up between index finger and thumb). This resulted in four groups of stimuli: natural object/power grasp, natural object/precision grasp, artificial object/power grasp, and artificial object/precision grasp. A complete list of the object names is provided in Appendix A and all pictures can be found online at https://osf.io/p9fje/. An additional set of pictures of 5 natural objects and 5 artifacts was created for practice.

We used a response device that we named the *Grabbit* (Roest, Pecher, Naeije, & Zeelenberg, 2016) which was inspired by and functionally equivalent to Bub et al.'s (2008) *Graspasaurus*. This device consists of an MDF (multi-density fibreboard) base that was set up with two graspable aluminum cylinders on it. A thin cylinder (diameter 1 cm) was used which afforded a precision grasp and a thick cylinder (diameter 6 cm) was used which afforded a power grasp. Both cylinders had a height of 14 cm. They were placed on the board at a 20 cm distance from each other. In order to record the grasping response we used a *Makey Makey* ® (JoyLabz LLC), a device that converts objects into computer keys by sending a keyboard message to the computer when the electrical circuit between its ground and another part is closed. An electrode was placed on the non-dominant hand of the participant so that the circuit was closed whenever the participant touched one of the cylinders. For safety reasons, a galvanic isolation was placed between the *Makey Makey* and the computer. Furthermore, because participants started the trial with their finger on the *b* key, a keyboard was placed in front of the *Grabbit* in such a way that the *b* key had the same distance to both cylinders. The complete setup is shown in Fig. 1.

1.1.3. Procedure

Participants were tested individually in a quiet room while the experimenter was present. Participants were placed in front of a regular computer, the *Grabbit* and a keyboard. The relative position (left or right) of the two cylinders on the base of the *Grabbit* was counterbalanced across participants. The experiment consisted of two tasks: a categorization task and a surprise free recall task. Participants started with the categorization task. At the beginning of the experiment, participants received written instructions about the task including which cylinder to grasp when making a natural or artificial judgment. The assignment of natural and artificial responses to the two cylinders was counterbalanced across participants. Participants received no information about the free recall memory task. Each categorization trial started with the presentation of a fixation cross. Participants were instructed to respond to the fixation cross by pressing the *b* key on the keyboard using their dominant hand in order for the object to appear in the center of the screen. They were instructed to hold the key until they made their response. The object disappeared immediately after release of the *b* key. Subjects had to decide if the object shown was a natural or an artificial object by grasping either the small cylinder or the big cylinder depending on the instruction they received. This resulted in four conditions: large object/power grasp response (compatible), large object/precision grasp response (incompatible), small object/power grasp (incompatible), small object/precision grasp (compatible). If the response was incorrect, the participant received feedback "*FOUT*" (*incorrect*) on the computer screen for 750 ms. A blank screen ISI of 1000 ms was presented after the response (or feedback, if an error had been made) before the next trial began. The categorization task consisted of 160 trials in total (the set of 80 objects was presented twice, each time in a different random order). Participants received 10 practice trials ahead of the experimental trials. Participants were instructed to respond as fast and accurate as possible.

After completion of the categorization task, participants immediately received written instructions for the unexpected free recall task. They were instructed to recall the objects they had previously seen. They had 10 min to type in the computer all the objects they could remember.

1.1.4. Design

A 2 (object size: power grasp affordance/precision grasp affordance) × 2 (response grasp: power grasp/precision grasp) within-subjects design was used. Three dependent measures were used to characterize performance in the semantic categorization task (natural vs. artifact decision): release time (the time between onset of the object picture and release of the *b* key), movement time (the time between release of the *b* key and grasping the *Grabbit* response element) and accuracy of the response (i.e., whether the correct response element was grasped). The dependent measure for the free recall task was the number of correctly recalled object names.

1.2. Results and discussion

1.2.1. Semantic categorization

Only trials on which the participants made a correct natural/artifact decision were included in the analysis of reaction times. In addition, responses with latencies below 100 ms and above 2000 ms for releasing the *b* key and grasping latencies above 2000 ms were excluded (2.88% of the correct responses). Mean reaction times in ms for each condition (compatible/incompatible) for each participant were calculated for release time and movement time and can be found at https://osf.io/p9fje/. The means and their standard errors are shown in Table 1.

We compared the means for movement time for the compatible and incompatible conditions in a paired sample *t*-test and in addition calculated the JZS Bayes Factor (*BF*), which is the ratio of $p(D \mid H_0)$, the probability of observing the data under the null hypothesis, and $p(D \mid H_1)$, the probability of observing the data under the alternative

Fig. 1. Set-up of the keyboard, Grabbit, and screen (left) and close-up of the response cylinders (right).

Table 1
Average release time (in ms), movement time (in ms) and accuracy in the semantic categorization task for compatible and incompatible conditions in Experiments 1–3.

	Experiment 1		Experiment 2		Experiment 3		Experiment 4	
Condition	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Release time								
Compatible	506	23	625	22	501	19	606	23
Incompatible	511	24	631	21	509	19	621	25
Movement time								
Compatible	395	16	407	16	599	17	369	15
Incompatible	407	18	418	16	596	17	380	16
Accuracy								
Compatible	0.99	0.002	0.97	0.003	0.99	0.002	0.99	0.002
Incompatible	0.98	0.003	0.97	0.004	0.99	0.002	0.99	0.002

Note. M = mean, SE = standard error of the mean.

hypothesis.[1] The Bayes Factor thus provides a relative measure of the extent to which the data provide evidence for the null hypothesis of no effect or the alternative hypothesis (Rouder, Speckman, Sun, Morey, & Iverson, 2009). Bayes Factors were calculated using JASP (Love et al., 2015). Movement time was faster when object size and grasp were compatible than when they were incompatible, $t(39) = 3.20$, $p = 0.003$ (see Table 1). The mean difference (-12.78, 95% CI [-20.57, -4.65]) demonstrated a medium effect size, $d = 0.51$, $BF_{10} = 12.50$. The Bayes Factor thus indicated that the data provide 12.50 times more evidence for the alternative hypothesis than for the null hypothesis of no effect. Additionally, participants made fewer errors when object size and grasp were compatible than when object size and grasp were incompatible, $t(39) = 2.37$, $p = 0.023$. The mean difference (0.01, 95% CI [0.001, 0.016]) demonstrated a medium effect size, $d = 0.37$, $BF_{10} = 2.02$. The effect of condition on the mean release times nearly reached significance, $t(39) = 1.98$, $p = 0.055$, (mean difference = -4.88, 95% CI [-9.87, 0.10], $d = 0.31$), $BF_{01} = 1.01$.

1.2.2. Free recall

Two experimenters first scored the accuracy of the recalled items (blind to condition) separately. All correct answers were scored as 1 and all incorrect scores were scored as 0. A 96.72% agreement between experimenters was reached. After discussion, all disagreements were resolved. Most of the disagreement regarded the scoring of the response *noot* (English translation: *nut*). In some cases participants only wrote down the category name *noot* while there were several different exemplars of this category included in the set of objects (e.g., *walnut*, *pistachio*). However, because the objects belonged to the same condition (natural judgment and precision grasp) and to the same compatibility condition the choice for one or the other exemplar had no consequences for the outcome of the analysis. We therefore counted '*noot*' as one correct answer. Finally, we calculated the proportion of accurately recalled objects for each participant in each condition.

To test our main hypothesis concerning the effect of grasp compatibility on long-term memory, we analyzed the mean number of correctly recalled objects for each condition (compatible/incompatible) with a paired samples t-test. Means and their standard errors are shown in Table 2. No significant difference between the conditions was observed, $t(39) = 1.10$, $p = 0.277$ (mean difference = 0.01, 95% CI [-0.015, 0.051], $d = 0.17$), $BF_{01} = 3.33$.

In addition to the main analysis, we did an exploratory analysis to test if the compatibility between object size and grasp type had a differential effect on recall accuracy for the object's category. That is, recall of artificial objects may suffer more from incompatibility between the size of the object and the type of grasp because memory for artificial objects might depend more on motor actions than memory for natural objects (but see Bukach, Bub, Masson, & Lindsay, 2004). To investigate this possible interaction, a 2 (category) by 2 (compatibility) repeated measures ANOVA was performed on recall accuracy. Means and their standard errors are shown in Table 3. Results showed no significant interaction between compatibility and category on recall accuracy, $F(1, 39) = 2.31$, $p = 0.136$, partial $\eta^2 = 0.03$, $BF_{01} = 1.49$.

To summarize, we found grasp compatibility effects in the categorization task, thereby replicating the results found by Tucker and Ellis (2004). The observed compatibility effects indicate that visual objects potentiate compatible grasp responses. However, we did not

[1] Throughout this paper we report BF_{01} if the evidence is in favour of H_0 and BF_{10} if the evidence is in favour of H_1, because this results in BFs equal or higher than 1. The Cauchy prior width was set to 0.707.

Table 2
Free recall proportions for compatible and incompatible conditions in Experiments 1–3.

	Experiment 1		Experiment 2		Experiment 3	
	M	*SE*	*M*	*SE*	*M*	*SE*
Compatible	0.30	0.02	0.25	0.01	0.25	0.01
Incompatible	0.28	0.02	0.24	0.02	0.26	0.01

Note. M = mean, SE = standard error of the mean.

Table 3
Free recall proportions for each category (artificial/natural) for compatible and incompatible conditions in Experiments 1–3.

	Experiment 1		Experiment 2		Experiment 3	
	M	*SE*	*M*	*SE*	*M*	*SE*
Artificial						
Compatible	0.23	0.02	0.18	0.01	0.19	0.01
Incompatible	0.24	0.02	0.20	0.02	0.20	0.02
Natural						
Compatible	0.37	0.03	0.32	0.02	0.31	0.02
Incompatible	0.33	0.02	0.28	0.02	0.32	0.02

Note. M = mean, SE = standard error of the mean.

find the hypothesized effect of compatibility on long-term memory. This contrasts with the findings of Van Dam et al. (2013) who found that compatible movements after initial encoding resulted in better memory performance compared to incompatible movements. It is possible that in our experiment, participants focused their attention mostly on visual characteristics of the objects, because they were presented as pictures, rather than deeper conceptual knowledge. Tucker and Ellis (2004; see also Bub et al., 2008) showed that similar grasp compatibility effects were observed for object pictures and object names. We hypothesized that categorization might rely on conceptual knowledge more strongly for words than pictures. This might explain the difference in findings between Van Dam et al. and our Experiment 1. Therefore we used object names rather than object pictures as stimuli in Experiment 2. This would be a stronger test for the hypothesis that motor action is integral to conceptual knowledge. We expect that incompatibility between object size and grasp type, and thus interference in motor activation, will lead to a less complete memory trace and hence worse recall.

2. Experiment 2

2.1. Method

2.1.1. Participants

Forty psychology students participated in the experiment in exchange for course credit. Three participants were left-handed. None of the participants had participated in Experiment 1.

2.1.2. Materials and procedure

The stimuli were the words denoting the objects used in Experiment 1. We replaced three words because these were homonyms. The object names (and their replacements in parentheses) are listed in Appendix A. The procedure was identical to the procedure used in Experiment 1.

2.2. Results and discussion

2.2.1. Semantic categorization

The same outlier criteria were used as in Experiment 1. This resulted in 0.75% of the responses being classified as outliers. As shown in Table 1, movement time was faster in the compatible condition than in the incompatible condition, $t(39) = 2.57$, $p = 0.014$. The mean difference (-11.74, 95% CI [-20.98, -2.50]) demonstrated a medium effect size, $d = 0.41$, $BF_{10} = 3.03$. No significant difference between conditions was observed for release time and accuracy, $t(39) = 1.40$, $p = 0.168$, $t(39) = 0.19$, $p = 0.848$ (mean difference = -5.10, 95% CI [-12.44, 2.24], $d = 0.22$), $BF_{01} = 2.36$, and $t(39) = 0.98$, $p = 0.333$ (mean difference = 0.00, 95% CI [-0.005, 0.013], $d = 0.16$), $BF_{01} = 3.75$, respectively.

2.2.2. Free recall

There was a 98.96% agreement between experimenters for scoring the accuracy of the recalled items. After discussion, all disagreements were resolved. We calculated the mean number of correctly recalled objects for each participant for each condition (compatible/incompatible) as shown in Table 2. A paired samples t-test revealed no significant difference between the conditions, $t(39) = 0.89$, $p = 0.381$ (mean difference = 0.01, 95% CI [-0.02, 0.05], $d = 0.12$), $BF_{01} = 4.50$.

Finally, we did an exploratory analysis to test if the compatibility between object size and grasp type had a differential effect on recall accuracy for the object's category. A 2 (category) by 2 (compatibility) repeated measures ANOVA was performed on recall accuracy. Means and their standard errors are shown in Table 3. There was a significant interaction between compatibility and category on recall accuracy, $F(1, 39) = 4.70$, $p = 0.04$, partial $\eta^2 = 0.11$, $BF_{10} = 1.04$, suggesting that recall of natural objects was affected more by incompatibility between object size and grasp type compared to artificial objects. The pattern was opposite to what we expected, because it is generally assumed that functional knowledge is more important for artifacts than natural objects (Cree & McRae, 2003; Gainotti, 2000; Warrington & Shallice, 1984; but see Bukach et al., 2004). Follow-up t-tests, however, showed no significant compatibility effects for either category, $t(39) = 0.93$, $p = 0.361$, $BF_{01} = 3.94$ for artifacts, and $t(39) = 1.59$, $p = 0.121$, $BF_{01} = 1.86$ for natural objects. Thus, the absence of compatibility effects in the main analyses does not seem to be the result of differences between natural objects and artifacts.

To summarize, as in Experiment 1, we found a significant grasp size compatibility effect for natural-artificial decisions, which suggests that action information not only becomes active upon recognizing objects pictures but also upon reading words denoting manipulable objects. This effect is consistent with the view that the grasp action associated with the object is part of the conceptual representation of the object (Bub et al., 2008; Bub & Masson, 2010b; Tucker & Ellis, 2004). Grasp compatibility, however, did not influence long-term memory for objects as participants recalled an equal number of objects from the compatible and incompatible conditions.

A possible explanation for the absence of compatibility effects in memory is that the task requirements still allowed activation and possibly encoding of the correct action even when the response was incompatible. In Experiments 1 and 2 the object was shown before participants made a grasping response. If actions are activated automatically as part of the object concept, participants may have had enough time to activate potential actions with the object, regardless of the grasping action that was required to make a response, because the response occurred only after activating the concept.[2] In Experiment 3, we therefore changed the timing of grasp and stimulus presentation so that potential interference from an incompatible grasp occurred from the onset of stimulus presentation. Specifically, participants held one of the cylinders from the onset of stimulus presentation until they moved their hand to make a response by pressing a key. Grasp incompatibility would presumably interfere with the activation of the object's associated grasp. As such, if action supports long-term memory, this

[2] Note, however, that Van Dam et al. (2013) did find an effect of action compatibility for actions performed after initial study. We would therefore still have expected such an effect in our Experiments 1 and 2.

interference would lead to a less complete memory trace of the object in long-term memory and hence worse recall.

3. Experiment 3

3.1. Method

3.1.1. Participants

Forty psychology students of the Erasmus University Rotterdam participated in the experiment for course credits. Three participants were left-handed. No participant had participated in the preceding experiments.

3.1.2. Materials

The materials and the set-up of the *Grabbit* in Experiment 3 were identical to those used in Experiment 1.

3.1.3. Procedure

The procedure of the categorization task was changed, and in particular the moment of motor-interference. Each categorization task trial started with the presentation of a fixation cross 12.5 cm left or right from the center of the computer screen, at the approximate left-right position of the intended cylinder on the *Grabbit*. Participants were instructed to respond to the fixation cross by grasping the cylinder on the same side (left or right) as the fixation cross. Upon grasping, a picture of an object appeared on the screen. Then subjects decided if the object shown was natural or artificial and responded by pressing the *y* key (natural) or the *b* key (artificial) on the keyboard. The participant received feedback "*FOUT*" (*incorrect*) on the screen for 750 ms if an incorrect response had been made. A blank screen ISI of 1000 ms was presented after the response (or feedback, if an error had been made) before the next trial began. Five objects were presented in each combination of fixation position, object size, object category, and cylinder size. Four different versions were created to counterbalance items across fixation position and cylinder size. Each participant received one of these counterbalanced versions. Cylinder position (thick cylinder on the right, thin cylinder on the left and vice versa) was also counterbalanced across participants, resulting in a total of eight counterbalanced versions. The experiment started with ten practice trials ahead of the experimental trials. Participants were instructed to respond as fast and accurate as possible.

3.1.4. Design

A 2 (object size: power grasp affordance/precision grasp affordance) × 2 (response grasp: power grasp/precision grasp) within-subjects design was used. Three dependent measures were used for the categorization task: cylinder release time, movement time (the time between release of the cylinder and the key press), and response accuracy. The dependent measure for the free recall task was the number of correctly recalled objects.

3.2. Results

3.2.1. Semantic categorization

Only correct trials were included in the RT analyses. Response latencies below 100 ms and above 2000 ms for releasing the cylinders and response latencies for pressing the *y* and *b* key above 2000 ms were excluded (1.07% of the correct RTs). Means and their standard errors are shown in Table 1.

A paired samples *t*-test on the mean release times showed significant faster release times for compatible conditions compared to incompatible conditions, $t(39) = 3.16$, $p = 0.003$. The mean difference (− 8.45, 95% CI [− 13.86, − 3.05]) demonstrated a medium effect size, $d = 0.50$, $BF_{10} = 11.50$. No significant differences between conditions on movement time and accuracy were observed, $t(39) = 0.76$, $p = 0.452$ (mean difference = 3.25, 95% CI [− 5.40, 11.90], $d = 0.12$), $BF_{01} = 4.48$ and $t(39) = 0.81$, $p = 0.421$ (mean difference = 0.00, 95% CI [− 0.002, 0.006], $d = 0.13$), $BF_{01} = 4.30$, respectively. Thus, the compatibility effect was only present in the release times.

3.2.2. Free recall

There was a 98.96% agreement between experimenters for scoring the accuracy of the recalled items. After discussion, all disagreements were resolved. Means and their standard errors are shown in Table 2. Of primary interest was the effect of compatibility on long-term memory. We therefore calculated the mean number of accurately recalled objects for each participant and each condition (compatible/incompatible). A paired samples *t*-test revealed no significant difference between the conditions, $t(39) = 0.97$, $p = 0.340$ (mean difference = − 0.01, 95% CI [− 0.043, 0.015], $d = 0.15$), $BF_{01} = 3.80$.

In addition to the main analyses, we did an exploratory analysis to test if the compatibility between object size and grasp type had a differential effect on recall accuracy for the object's category. A 2 (category) by 2 (compatibility) repeated measures ANOVA was performed on recall accuracy. Means and standard errors are shown in Table 3. No significant interaction between compatibility and category on recall accuracy was observed, $F(1, 39) = 0.00$, $p = 0.97$, partial $\eta^2 = 0.00$, $BF_{01} = 4.44$.

4. Combined analysis of Experiment 1–3: recall data

To have a more powerful test of the grasp compatibility effect on memory, we performed an additional analysis in which we combined the recall data from Experiments 1 to 3. The 2 (compatibility) by 3 (Experiments) mixed ANOVA showed no difference in recall between compatible and incompatible objects, $F(1, 117) = 0.41$, $p = 0.53$, partial $\eta^2 = 0.00$, (mean difference = 0.01, 95% CI [− 0.013, 0.025]), $BF_{01} = 5.83$. In addition, no significant interaction between compatibility and category on recall accuracy was observed, $F(1, 118) = 0.20$, $p = 0.65$, partial $\eta^2 = 0.00$, $BF_{01} = 7.98$. Thus, grasp compatibility did not have an effect on object recall.

One concern that might be raised is that overall free recall performance in Experiments 1–3 was too low (perhaps due to a somewhat long list length) to detect an effect of the critical manipulation. It should be noted though that the observed performance levels are not atypical for free recall (e.g., Murdock, 1962; Roberts, 1972). Moreover, performance was clearly off floor; all participants did recall at least one of the items presented in the categorization task. Furthermore, many studies with similar levels of recall performance (i.e., around 20–30%) have found effects of the critical manipulation (e.g., Burns, 1990; Engelkamp, Seiler, & Zimmer, 2004; Engelkamp & Zimmer, 1997; Malmberg & Shiffrin, 2005). Thus, it appears unlikely that the lack of an effect of grasp compatibility on free recall was due a floor effect.

5. Experiment 4

We studied recognition memory in Experiment 4 because Van Dam et al. (2013) found an effect of motor action on long-term episodic memory for words in a single item recognition task. Possibly, a recognition memory task is more sensitive to motor information than free recall. In free recall, participants have to retrieve items from long-term memory while little information is presented to support retrieval. In a recognition task, items do not have to be generated from memory, but rather items are presented to the participant at test and participants have to decide whether or not they have seen the item earlier on during the experiment. The visual presentation of stimuli and subsequent activation of action-related information during test may boost the involvement of motor system in episodic memory.

5.1. Method

5.1.1. Participants

Forty psychology students of the Erasmus University Rotterdam participated in the experiment for course credits. Six participants were left-handed. No participant had participated in the preceding experiments.

5.1.2. Materials

The same 80 critical stimuli were used as in Experiment 1. We rotated some of the pictures to align the orientation of the object with the orientation of the response cylinders. In addition, we selected 80 object pictures that were used as foils in the recognition memory task. The foils consisted of different objects that were from the same categories as the target objects (e.g., fruits, tools, etc.) with 20 each in the four combinations of natural objects/artifacts and power/precision grip. To prevent interference from performing a hand action in the recognition task we used two foot pedals to collect recognition responses.

5.1.3. Design and procedure

The design and the set-up of the *Grabbit* in Experiment 4 were identical to those used in Experiment 1. The only difference was that after the categorization task, an unexpected recognition task was used instead of a recall task. In the recognition task, pictures of objects were presented on the screen and participants decided whether the object picture had been presented during the categorization task. Each picture was preceded by a central fixation (+) of 250 ms. The picture remained on the screen until the participant responded by pressing the right foot pedal for targets and the left pedal for foils. The next trial started 1000 ms after response. Target and foil pictures were presented a random order.

5.2. Results

5.2.1. Semantic categorization

Only correct trials were included in the RT analyses. Response latencies below 100 ms and above 2000 ms for releasing the *b* key and response latencies for grasping the cylinders above 2000 ms were excluded (1.31% of the correct RTs). Means and their standard errors are shown in Table 1.

A paired samples *t*-test on the mean release times showed significant faster release times for the compatible condition than for the incompatible condition, $t(39) = 2.61$, $p = 0.013$. The mean difference (-14.38, 95% CI [-26.30, -3.35]) demonstrated a medium effect size, $d = 0.41$, $BF_{10} = 3.33$. Movement times were also faster for the compatible condition than for the incompatible condition, $t(39) = 3.85$, $p < 0.001$ (see Table 1). The mean difference (-11.27, 95% CI [-17.19, -5.35]) demonstrated a medium effect size, $d = 0.61$, $BF_{10} = 65.04$.

5.2.2. Recognition

Hit and false alarm rates were used to calculate *d*-primes. A paired samples t-test showed that *d*-prime for objects that had been presented in the compatible condition (2.74) did not differ from that for objects that had been presented in the incompatible condition (2.61), $t(39) = 1.64$, $p = 0.110$. The mean difference was 0.14 (95% CI [-0.03, 0.31]), $d = 0.26$, $BF_{01} = 1.73$. In addition, no significant interaction between compatibility and category on d-primes was observed, $F(1, 39) = 1.30$, $p = 0.261$, partial $\eta^2 = 0.03$, $BF_{01} = 2.75$.

6. General discussion

In three experiments, we investigated the influence of compatibility between the typical grasp size of an object and response grasp type on immediate semantic categorization and delayed free recall. In a fourth experiment we used a recognition memory task instead of free recall. We found that categorization responses were consistently faster in compatible than in incompatible conditions. In none of the experiments, however, did compatibility affect long-term memory. It is important to point out that the lack of an effect of grasp compatibility on long-term memory performance was accompanied by a compatibility effect in the semantic categorization task. It is thus not the case that compatibility had no effect at all on performance. The presence of compatibility effects in the categorization task, together with the absence of an effect on memory, even in the analysis that combined the results of the three recall experiments, suggests that the absence of a compatibility effect on long-term memory performance was not simply due to a lack of statistical power to detect an effect. In the immediate categorization task, we replicated earlier findings that visual and verbal object stimuli activate compatible grasp responses (Bub et al., 2008; Girardi et al., 2010; Masson et al., 2013; Tucker & Ellis, 2001, 2004).

In our experiments and previous ones grasp compatibility effects were found even though the grasp associated to the object was irrelevant for the semantic categorization task. Based on these and similar findings it is often suggested that actions are automatically activated during conceptual processing. This is consistent with the idea that conceptual representations consist of sensory-motor simulations of interactions with the concept. Here we investigated if action information supports long-term memory. We expected that incompatible grasps during encoding would interfere with the activation of object-related actions in memory and consequently result in a less complete memory trace and hence worse recall for those objects. Despite successful interference during the categorization task when the objects were encoded (providing a manipulation-check) the free recall and recognition results repeatedly did not show an effect of grasp compatibility on long-term memory. The present data therefore do not support the hypothesis that motor action supports long-term memory for object names or pictures of objects.

These findings do not converge with those of Van Dam et al. (2013). In their study, participants studied a list of familiar object names under explicit study instructions. Between study and memory test, participants performed an action that was compatible with some objects and incompatible with other objects. They found that memory was better for the compatible than incompatible objects. Because the action was performed after encoding in an ostensibly unrelated filler task, the authors concluded that the motor system plays a role in the consolidation of semantic representations. It is possible that motor actions that are performed during initial memory encoding have no effect on memory, but motor actions that are performed during subsequent memory consolidation facilitate memory for compatible objects.

Although the null effects suggest that motor actions do not play a role in memory for objects, they might also indicate a mismatch between the theoretical account and the particular method used to measure the presumed mechanism. For example, it is possible that the stimuli we used were not optimally suited for testing the prediction that motor actions support memory for objects. We therefore explored the possibility that motor actions are more important for artifacts than natural objects, as has been suggested by the literature on neuropsychological patients with a category-specific impairment for semantic knowledge. Some researchers have suggested that selective impairment of categories might be due to differences in the contribution of sensory-motor information to the representation of these categories (Cree & McRae, 2003; Gainotti, 2000; Warrington & Shallice, 1984; but see Bukach et al., 2004). Specifically, natural objects may be defined more by perceptual features whereas artifacts are defined more by motor actions that are related to their functional properties. In none of the four experiments, however, did we find support for this explanation. Memory for artifacts was not influenced more by grasp compatibility than memory for natural objects. We should note that the natural objects that we used were items that people often manipulate with their hands, such as fruits, for which activity in the left premotor cortex has been found to be more similar to that for manipulable artifacts than for nonmanipulable natural objects (Gerlach, Law, & Paulson, 2002). These findings speak against the explanation that finding a null effect in the present study is a consequence of using natural objects as stimuli.

One might also argue that incompatible grasps are more novel compared to compatible grasps and that the resulting salience of the incompatible grasp enhanced rather than impaired memory for the incompatible objects. The present null findings on memory might even be a result of the two opposing effects of novelty and interference. However, studies investigating multisensory memory do not support this idea. For example, Thelen, Talsma, and Murray (2015, see also Kim, Seitz, & Shams, 2008; Lehmann & Murray, 2005; Moran et al., 2013; Shams & Seitz, 2008) found that memory for pictures was better if they had been paired with a compatible sound than an incompatible sound during study, suggesting that salience due to incompatibility does not enhance memory.

Additionally, one might argue that our manipulation of compatibility may not have been strong enough to induce interference in long-term memory. In the categorization task, however, we obtained compatibility effects, indicating that the manipulation was strong enough to interfere with conceptual processing. A related objection might be that only two experiences of an incompatible grasp may not affect memory for familiar objects, because people will have had many compatible experiences with these objects before they came to our lab. The literature on episodic memory, however, shows many examples of experiments in which the specific encoding conditions of even a single encounter with a familiar stimulus affects memory for that stimulus. For example, studies on the encoding specificity principle (Thomson & Tulving, 1970) show that a pre-experimentally strong cue (e.g., *table*) becomes a weak cue after the target word (*chair*) has been studied in the context of a different associate (e.g., *glue*). Related findings of (sentence) context have been reported in many studies (e.g., Barclay, Bransford, Franks, McCarrel, & Nitsch, 1974; Light & Carter-Sobell, 1970; Zeelenberg, 2005). These findings suggest that, as expected, episodic memory is driven largely by specific encounters with a stimulus and not dominated by its general properties.

Related to this, the recent studies on multisensory memory mentioned above (Kim et al., 2008; Lehmann & Murray, 2005; Moran et al., 2013; Shams & Seitz, 2008; Thelen et al., 2015) showed that episodic memory for visual or auditory stimuli is enhanced by task-irrelevant stimuli in a different modality if they are conceptually congruent compared to incongruent. For example, memory for a picture of a *dog* was better if, during encoding, it had been paired with a *woof* sound than if it had been paired with a *dong* sound, even though participants were tested only on their memory for the pictures and thus the sound was irrelevant for the memory task. Our experiments are comparable to this manipulation except that the pictures were paired with congruent or incongruent actions rather than sounds. Thus, congruency in conceptual processing at encoding has been shown to affect retrieval. The obtained null results in the present study, however, still have to be interpreted carefully. It is possible that an effect of grasp compatibility on long-term memory could arise with a different manipulation than the one we used in the current study. If other studies using different manipulations reach the same conclusions as the present study, this would bolster the claim that motor actions do not support long-term episodic memory for objects.

The results presented here are in line with previous results from our lab (Pecher, 2013; Pecher et al., 2013; Quak et al., 2014) in which we did not find any evidence for a role of motor actions in visual short-term memory. Because representations in short-term memory might rely mostly on the maintenance of perceptual properties of the stimulus rather than conceptual knowledge, motor actions might be of little relevance in short-term memory for object pictures. The present results suggest, however, that motor actions also are not important for initial encoding of object representations in long-term memory. Results from other studies might seem to contrast with this conclusion. For example, the enactment effect demonstrates an advantage for enacted over observed actions in long-term memory (Engelkamp & Dehn, 2000; Engelkamp & Zimmer, 1997; Zimmer, Helstrup, & Engelkamp, 2000). When participants actively enact the action during learning of action phrases such as *lift the pen* or *smoke the pipe*, they have better memory for the phrases than when they only read or observe another person perform the action (Engelkamp & Dehn, 2000; Engelkamp & Zimmer, 1997; Zimmer et al., 2000). Superior memory for enacted items might be due to engagement of the motor system during encoding (Madan & Singhal, 2012). That this enactment effect is due to support from the motor system has been debated, however (Senkfor, Van Petten, & Kutas, 2008). Some have argued that enactment is merely another example of a more general phenomenon that memory is better for unusual items (McDaniel & Bugg, 2008; Peterson & Mulligan, 2010). The enactment effect, like other effects of unusualness, is present on mixed lists when some items are enacted by the participant and other items are enacted by the experimenter, but not on pure lists. This finding suggests that enactment makes the item more distinguishable from others because the participant gives the enacted item more attention at the cost of the other items during encoding or that the enacted items 'pop out' during retrieval. Thus, the enactment effect might not reflect a general supportive role of the motor system in long-term memory. Moreover, the difference in results between enactment effect studies and our current study might reflect a difference in focus on motor actions (see also Guérard et al., 2015). Possibly, effects of motor actions on memory are obtained only when the task explicitly draws attention to motor actions, suggesting that they are not encoded automatically.

To conclude, the current study replicated earlier findings of grasp compatibility for object pictures and names. This finding adds to the existing evidence for a relation between motor actions and object concepts. Despite this evidence for a motor compatibility effect, however, subsequent memory tests showed that motor compatibility had no effect on recall and recognition memory. Thus, the present data do not provide evidence that motor actions are automatically encoded in memory traces when participants encounter objects.

Appendix A. Stimulus materials used in Experiment 1–4

Large artifacts	Large natural objects	Small artifacts	Small natural objects
Bierpul (Beer Mug)	Aardappel (Potato)	Haarspeld (Hair Pin)	Aardbei (Strawberry)
Boor (Drill)	Appel (Apple)	Knoop (Button)	Blad (Leaf)
Champagnefles (Champagne Bottle)	Aubergine (Eggplant)	Krijtje (Crayon)	Braambes (Blackberry)
Koffiepot (Coffeepot)	Banaan (Banana)	Mascara (Mascara)	Druiven (Grapes)
Gewicht (Dumbell)	Bleekselderij (Celery)	Nietjes (Staples)	Eikel (Acorn)
Gieter (Watering Can)	Broccoli (Broccoli)	Oorbel (Earring)	Gamba (Gamba)
Hamer (Hammer)	Citroen (Lemon)	Paperclip (Paperclip)	Kers (Cherry)
Kaars (Candle)	Courgette (Zucchini)	Pil (Pill)	Koffieboon (Coffee Bean)
Kan (Jug)	Dennenappel (Pinecone)	Pincet (Tweezers)	Mossel (Mussel)

Kandelaar (Candle Holder)	Houtblok (Log)	Pleister (Adhesive Bandage)	Olijf (Olive)
Knoflookpers (Garlic Press)	Komkommer (Cucumber)	Potlood (Pencil)	Paardenbloem (Dandelion)
Maatbeker (Measuring Cup)	Mais (Corn)	Rietje (Straw)	Paddenstoel (Mushroom)
Ontstopper (Plunger)	Mango (Mango)	Ring (Ring)	Peterselie (Parsley)
Pan (Pan)	Paprika (Bell Pepper)	Schroef (Screw)	Pinda (Peanut)
Paraplu (Umbrella)	Peer (Pear)	Sigaret (Cigaret)	Pistache (Pistachio)
Spuitbus (Spraying Can)	Prei (Leek)	Snoepje (Candy)	Roos (Rose)
Steelpan (Saucepan)	Sinaasappel (Orange)	Spijker (Nail)	Sperzieboon (Green Bean)
Trekker (Squeegee)	Sla (Lettuce)	Veiligheidsspeld (Safety Pin)	Spruitjes (Sprouts)
Verfroller (Paint Roller)	Tak (Branch)	Wasknijper (Clothespin)	Veer (Feather)
Zaklantaarn (Flashlight)	Ui (Onion)	Wattenstaafje (Cotton Swab)	Walnoot (Walnut)

Note. Stimuli were presented as pictures in Experiments 1, 3, and 4, and as Dutch words in Experiment 2; English translations are provided in parentheses. In Experiment 2, the following items were replaced: Gewicht (Dumbell) → Jampot (Jam Jar), Trekker (Squeegee) → Zaag (Saw), and Eikel (Acorn) → Doperwt (Pea).

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